AFRL-PR-WP-TR-2000-2086

FEASIBILITY ANALYSIS FOR AN ENVIRONMENTAL NICKEL-METAL HYDRIDE AIRCRAFT BATTERY

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AUGUST 2000

FINAL REPORT FOR PERIOD 07 AUGUST 1997 – 15 AUGUST 2000

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 074-0188
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1. AGENCY USE ONLY (Leave blank)	**2. REPORT DATE** AUGUST 2000	**3. REPORT TYPE AND DATES COVERED** Final Report for 08/07/1997 – 08/15/2000		
4. TITLE AND SUBTITLE FEASIBILITY ANALYSIS OF AN ENVIRONMENTAL NICKEL-METAL HYDRIDE AIRCRAFT BATTERY				**5. FUNDING NUMBERS** C: F33615-96-D-5101 PE: 69199F PR: OAFP TA: 97 WU: 02
6. AUTHOR(S) JOHN R. FENTER				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) GRC INTERNATIONAL, INC MANUFACTURING OPERATIONS 2940 PRESIDENTIAL DRIVE, SUITE 390 FAIRBORN, OH 45324-6297				**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) PROPULSION DIRECTORATE AIR FORCE RESEARCH LABORATORY AIR FORCE MATERIEL COMMAND WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251 POC: DR. JOHN K. ERBACHER, AFRL/PRPB, (937) 255-7770				**10. SPONSORING / MONITORING AGENCY REPORT NUMBER** AFRL-PR-WP-TR-2000-2086
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.				**12b. DISTRIBUTION CODE**

13. ABSTRACT *(Maximum 200 Words)*

Nickel-Metal Hydride prismatic cells have been designed, fabricated, and characterized for performance across the temperature range of -40°C to + 70°C. The optimized designs were validated in controlled laboratory conditions and under simulated environmental testing conditions. All aspects of the cells were evaluated and selected optimization was designed into the cells to advance the Ni-MH technologies to attain the program target goals. Electrode formulations, processes, electrolyte percentages, separator materials and thickness, and assembly were evaluated in specific cell design configurations. The charging procedure and algorithms were determined and implemented. These test and evaluation conditions were recommended for repeatable charging and safety limits to independently confirm the performance of the prototype designed battery. One prototype battery was delivered having approximately 64 Wh/kg using cells with 43 Ah capacity at C/2. Among the key performance variables for this next generation battery are broad temperature range and minimal self-discharge. Both key performance variables were enhanced sufficiently to make the Ni-MH battery technology a strong alternative battery power source in military flight vehicles.

14. SUBJECT TERMS Aircraft Battery, Nickel-Metal Hydride, Rechargeable Battery			**15. NUMBER OF PAGES** 40
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** SAR
NSN 7540-01-280-5500			**Standard Form 298 (Rev. 2-89)** Prescribed by ANSI Std. Z39-18 298-102

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FOREWORD

The Air Force Strategic Environmental R & D program supported this effort to demonstrate an environmentally safe alternative form, fit, and function battery for the F-16 Pre-Block 40 main aircraft battery. The technical performance target was to achieve a specific energy density of 75Wh/kg for the More Electric Aircraft Generation II program.

The project was contracted under the Advanced Manufacturing Technology Feasibility Demonstrations, contract F33615-96-D-5101, in the Materials and Manufacturing Technology Directorate, Air Force Research Laboratory. Dr. John K. Erbacher, Air Force Research Laboratory, Propulsion Directorate, Battery Technology Branch provided technical guidance. Mr. Timothy Provens, Aeronautical Systems Center, Environmental, Safety, and Health Pollution Prevention Branch provided funding for the three-year effort.

Nickel-Metal Hydride (Ni-MH) prismatic cells have been designed, fabricated, and characterized for performance across the temperature range of –40°C to +70°C. The optimized designs were validated in controlled laboratory conditions and under simulated environmental testing conditions. All aspects of the cells were evaluated and selected optimization was designed into the cells to advance the Ni-MH technologies to attain the program target goals. Electrode formulations, processes, electrolyte percentages, separator materials and thickness, and assembly were evaluated in specific cell design configurations. The charging procedure and algorithms were determined and implemented. These test and evaluation conditions were recommended for repeatable charging and safety limits to independently confirm the performance of the prototype designed battery. Among the key performance variables for this next generation battery are broad operating temperature range and minimal self-discharge. Both key performance variables were enhanced sufficiently to make the Ni-MH battery technology a strong alternative to conventional battery power sources in military flight vehicles. Nickel-Metal Hydride battery technology is a technically compatible and environmentally improved alternative to existing nickel-cadmium and sealed lead-acid batteries in many Air Force system applications.

ACKNOWLEDGMENTS

The work performed under Contract F33615-96-D-5101, Delivery Order 23, was supported by the Propulsion Directorate of the Air Force Research Laboratory and funded by the USAF Strategic Environmental Research, Development, and Pollution Prevention programs, Aeronautical Systems Center, Wright-Patterson AFB, Ohio.

Mr. Timothy Provens from the Aeronautical Systems Center, ASC/ENVV, provided funding for the effort. Dr. John K. Erbacher of AFRL/PRPB, as the Air Force project manager, provided technical support and guidance. Mr. John R. Fenter of GRC International, Inc. was project manager; and Mr. Bryan C. Mazey of GRC International, Inc. provided technical assistance.

EXECUTIVE SUMMARY

For military airborne and ground applications, the mainstay in rechargeable batteries has been the vented nickel-cadmium (Ni-Cd) battery. Unfortunately, due to the heavy maintenance and upkeep requirements, use of these batteries is costing the Air Force an estimated $50 million per year. In addition, these batteries, and possible lead-acid alternatives, use hazardous materials targeted on the EPA 17 list for elimination from use in the US. The Secretary of the Air Force supports the minimization and/or elimination of these materials in the SAF/AQ Acquisition Policy Memorandum 94A-003, 23 Aug. 1994. Currently, there are no environmentally acceptable alternative batteries that meet EPA requirements, comply with the HQ USAF policy and meet user performance requirements. Recently, AFRL/PRPB funded Small Business Innovative Research (SBIR), in-house, and other research efforts to develop nickel-metal hydride (Ni-MH), lithium-ion and lithium polymer batteries as potential environmentally acceptable aircraft battery systems. Availability of commercial Ni-MH batteries, the environmental alternative to the Ni-Cd battery, prompted AFRL/PRPB to evaluate the capability of Ni-MH batteries to meet military aircraft requirements. This test program defined shortcomings of commercial Ni-MH batteries and areas of development needed for application to the More Electric Aircraft (MEA) and/or as a possible alternative to existing aircraft Ni-Cd and lead-acid batteries. The commercial batteries that were tested did not meet the military operating upper temperature range, charge/discharge capacity and high self-discharge requirements. This feasibility project addressed the limitations of the commercial metal hydride batteries and conducted performance demonstrations leading toward the insertion of metal hydride technology as an improved environmental alternative using the F-16 Pre-Block 40 Main Aircraft Battery (MAB) as the baseline configuration.

The project identified and analyzed a number of design concepts. The GRCI team, Electro Energy, Inc., Eagle-Picher Technologies, Inc., SAFT America, Inc., and Yardney Technical Products as subcontractors, assessed improvements to the F-16 MAB design using both bipolar and prismatic baseline battery concepts. Based on the modified designs, material studies to validate the design changes were identified. Two contractors, Electro Energy, Inc. for bipolar designs and SAFT America for prismatic designs, were selected to conduct material studies and validate their designs.

The materials studies were conducted to confirm the baseline cell and battery designs for both the bipolar and prismatic concepts and formulate a test plan for single cell and battery tests for performance comparisons. Multiple metal hydride alloys, electrolytes and nickel electrode formulations were selected and tested to ascertain cell capacity and temperature limitations and to determine the optimum electrochemical configurations to maximize single cell performance. Characterization of individual cells and analysis of the test results showed the performance of both the bipolar and the prismatic concepts were promising. Both Electro Energy, Inc. and SAFT America were selected for further scale up and design improvements.

By pursuing two different design concepts, Electro Energy, Inc. on the bipolar concept and SAFT America on the prismatic concept, the technical risk for success was considerably lower. However, only one design concept was planned to be selected for design optimization

and integration into a battery configuration after completion of comparative testing and evaluation.

New materials and combinations were evaluated for the positive Ni electrode, the negative metal hydride electrode, and the separator. The electrolyte was modified where appropriate. The cell size was scaled up from laboratory test samples to a size needed for battery integration. The test plans and conditions were specified to allow comparison between the technologies and the designs. A common test matrix for both cell concepts was defined for cell capacity measurements, ambient life cycle, and environmental life cyc le measurements. A number of cell designs were evaluated under life cycle testing, charging and discharge performance versus temperature, and charge retention or self-discharge over 7 days versus temperature. Sample cells of each optimum cell concept were delivered for performance verification testing. With the assistance of a Technical Advisory Committee, SAFT America was selected to continue based on cell performance and reduced technical risk for battery assembly and integration.

Using the final design of the best cell at this juncture, a number of first article test sets composed of four cells were delivered for test. A detailed test plan, test procedures, and characterization of the test sets provided data for analysis leading to the battery design. The characterization data verified the earlier design predictions, developed performance data for charging and discharging against temperature and for self-discharge performance. The characterization data and test procedures formed the basis to define a test plan. The test plan of four cells for laboratory testing correlated as much as possible to the F-16 battery load profile or to known critical use conditions. All final design changes were incorporated into the pre-prototype, baseline, nickel-metal hydride battery. Charge monitoring guidance for the pre-prototype baseline battery was determined for safety and handling. One pre-prototype battery with a test plan was delivered for verification of performance parameters shown in Table 1.

Table 1 SAFT Ni-MH Battery Parameter Values Achieved

Nominal Voltage (V)	**24**
Rated Capacity (Ah)	**43**
Current (A)	**48**
Operating Temperature Range (°C)	**-40 to +71 (with heaters)**
Typical Battery Energy at C/2 (Wh)	**1,126**
Typical Specific Energy Density (Wh/kg)	**64**
Typical Volumetric Energy Density (Wh/l)	**127**
Total Battery Weight (kg {lb})	**17.7 {39}**
Maintenance Interval	**Maintenance Free**
Self-Discharge (<25% over 7 days)	**25% for T < 40°C**

1.0 INTRODUCTION

Nickel-MetalHydride battery technology is a technically compatible and environmentally improved alternative to existing nickel-cadmium and sealed lead-acid batteries in many Air Force system applications. One particularly viable alternate technology to the Ni-Cd and Pb-acid batteries is Nickel-MetalHydride (Ni-MH). Ni-MH batteries are under evaluation for potential application as a replacement power source for the existing Ni-Cd and Pb-Acid batteries currently used by the USAF. Besides being environmentally friendly and posing no threat in the event of operator exposure, advantages of metalhydride batteries over the presently used Ni-Cd and Pb-acid technologies include; higher efficiency per unit volume, higher energy density, lower periodic maintenance requirements, and higher specific power output.

This Air Force sponsored project with GRC International was to develop and demonstrate a sealed, maintenance free, 24-25 volt, Ni-MH aircraft battery that meets the following requirements:

> An environmentally safe alternative form, fit, and function battery for the F-16 C/D Pre-Block 40 main aircraft battery in accordance with the existing battery performance specification,
>
> A desired energy density of 75 Wh/kg for the More Electric Aircraft.

The Air Force Research Laboratory and the Air Force Strategic Environmental R & D program supported this effort with the target performance parameters for a final battery as listed in Table 2.

Table 2 Environmental Ni-MH Battery Performance Parameters

Nominal Voltage (V)	**28**
Capacity (Ah)	**50**
End of Life Capacity (Ah)	**18 (Maintained at 14.5)**
Current (A)	**48 (Maximum)**
Operating Temperature Range (°C)	**-40 to +71**
Battery Energy at C/2 (Wh)	**1,325**
Specific Energy Density (Wh/kg)	**75**
Volumetric Energy Density (Wh/l)	**177**
Total Battery Weight (kg {lb})	**18.18 {40}**
Mean Time Between Failures (MTBF)	**>6000 h**
Maintenance Interval	**Maintenance Free for Three Years**
Self-Discharge (<25% over 7 days)	**All Operating Temperatures**

2.0 DESIGN STUDIES

The developmental nature of this project required a broad assessment of industry activities and state-of-the-art Ni-MH batteries. In order to obtain an assessment of different designs, materials, and fabrication experience, an early study and analysis was conducted to define the benefits and limitations of differing approaches and to determine the companies having the strongest technical group to bring the technical advances together into a military aircraft application. A solicitation for a design and conceptual study was initiated with four companies listed in Table 3.

Table 3 Concept Studies Subcontractors

Yardney Technical Products, Inc. Pawcatuck, CT 06379 (860) 599-1100	Electro Energy, Inc. (EEI) Danbury, CT 06810 (203) 797-2697
Eagle-Picher Industries, Inc. (EPI) Joplin, MO 64802 (417) 623-8333	SAFT America, Inc. Cockeysville, MD 21030 (410) 771-3200

The goals and overall program objectives were presented to each of the four companies. Although all four companies concluded that Ni-MH could conceivably supply the high energy and power applications demanded by the F-16 aircraft battery, their specific approach, design, and material composition required to fulfill this objective differed greatly.

A Technical Advisory Committee (TAC) was established to advise GRCI and the program managers as a means to evaluate the work proposed by each of the subcontractors. At the conclusion of Concept Studies, the TAC conferred for a formal source selection review and evaluated the technical presentation materials from each of the subcontractors. The source selection process evaluated the capabilities of the subcontractors using the following factors to determine technical merit and likelihood of successfully completing the effort.

1. ***Technical Aspects***; Cell design, battery design material studies, single cell studies, baseline battery studies, and prototype MHAB.
2. ***Merit of Technical Approach***; These factors included information such as previous studies, findings, data results of battery, single cell and material research along with current avenues of chemical and battery technology being explored.
3. ***Specific Aspects of Metal Hydride Battery and Cell Operation***; Cathode, anode, electrolyte, case materials, load profiles, power requirements, charger interface, and performance-over-temperature range.
4. ***Risk Mitigation Strategies***; Such as alternative approaches and materials.
5. ***Planning Requirements***; Schedule by phase and task along with manhour allocation, materials estimate, and travel requirements.

6. ***Program Management Factors***; Overall program organization, potential risk areas to be addressed, expected future outcome and the potential effects on schedule, success, and delivery.

7. ***Other/Additional Factors***; Cost share (if any), amount and type of cost share, and supplemental work proposed, if any.

Based on the source selection committee's scoring results and subsequent discussion and review of all materials, the TAC was unanimous in their decision that Electro-Energy Inc. and SAFT America provided the strongest technical approaches while simultaneously giving the project reduced technical risk with two design alternatives.

3.0 TECHNICAL DIRECTION

The two design types were chosen to cover alternative designs and material possibilities and also provided two technical approaches for military applications. One was a conventional cell design by SAFT America called prismatic having flat rectangular electrodes and separators that give a compact design with flexibility for assembly into batteries meeting differing performance requirements. A second design by Electro Energy is called bipolar. The bipolar concept for Ni-MH batteries are cells stacked together without interconnecting terminals in a compact arrangement. Both concepts were considered technically sound and capable of maturing toward the production of environmental friendly, rechargeable, aircraft batteries.

3.1 SAFT – PRISMATIC

The SAFT design was a conventional battery design called prismatic having flat rectangular electrodes and separators that give a compact design with flexibility for assembly into batteries meeting differing performance requirements (Figure 1).

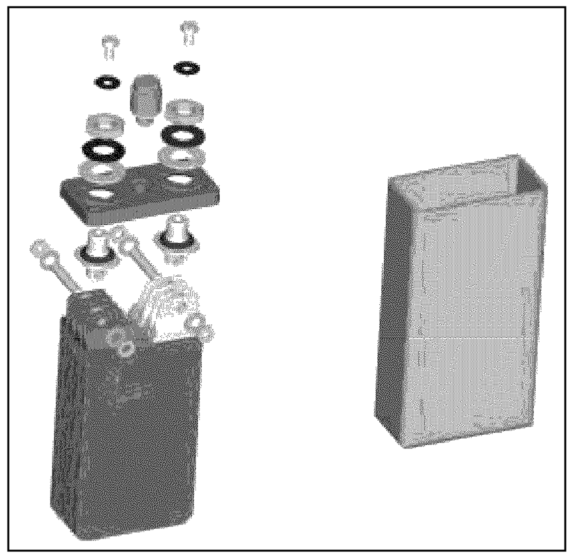

Figure 1 Exploded View of a Ni-MH Cell Showing Assembly Detail

3.2 EEI – BIPOLAR

The Electro Energy design is called bipolar. The bipolar concept for Ni-MH batteries has been described in a number of patents over the last few years. Bipolar cells are stacked together without interconnecting terminals which provide higher energy density and potentially lower cost than the conventional designs (Figure 2).

3.3 MATERIALS

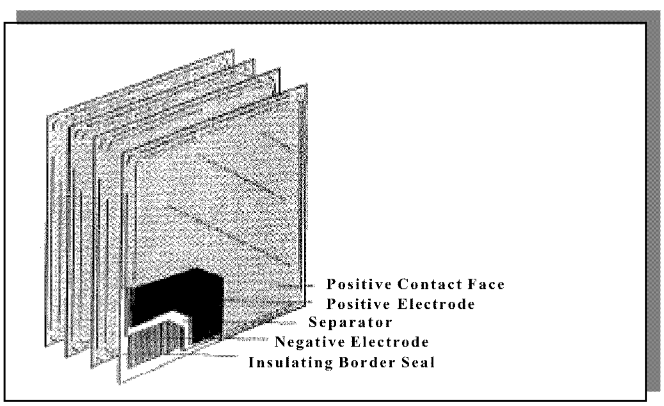

Figure 2 Bipolar Cell Schematic

The metal hydride material constitutes the negative electrode. The metal hydride of choice for this project is the class of intermetallics known as AB_5 where A is a strong hydride forming component and B is a weak hydride former. The A component is lanthanum or a less expensive alloy of the lanthanide series called mischmetal: an unrefined mixture of rare earth metals including lanthanum, cerium, praseodymium, and neodymium. Compositions of mischmetal depend

on the source of the ore and are not expected to be identical between batches. The B component is nickel or an alloy of nickel and the transition metals, cobalt, manganese, and aluminum. These metals form an AB_5 alloy that absorbs hydrogen. Cerium improves the corrosion resistance of the metal hydride and reduces the capacity decay when cycling. Cobalt improves the high temperature delivered capacity of the positive electrode. Thin electrodes give enhanced performance for low temperature delivered capacity. Low temperature performance is impacted by the particular metal hydride alloy used which controls the transport of hydrogen in the lattice.

3.3.1 Electrodes

The electrodes were composed of a conductive network that was processed with a slurry of either positive electrode material, $Ni(OH)_2$, or the negative electrode material, the lanthanum-rich mischmetal hydride composition of rare-earth transition metal hydrides. The strips containing the slurry are dried and laminated to a specified thickness. The thickness and weight of active material in the electrodes are critical to performance as are the relative number of negative to positive electrodes.

3.3.2 Separators

Separator materials were purchased from different sources. The materials hold the electrolyte but are inert to the electrochemical activity of the cell. The thickness and weight are critical to the performance of the cell.

3.3.3 Electrolytes

The electrolytes were based on KOH.

4.0 EARLY CELL DESIGNS

After 18 months into the effort, the results of the two subcontractors were reviewed and evaluated. Support from the TAC provided additional expert opinion and insight into the performance demonstrated to date and the projections for further advancement by each subcontractor. The following paragraphs summarize the early cell design results of SAFT America and Electro Energy.

4.1 SAFT AMERICA - PRISMATIC CELL DESIGN

SAFT evaluated many materials and defined several prismatic cell designs that satisfied all the performance requirements. The characterization data of cell charge and discharge capacity versus temperature, ambient cyclic testing at 50% depth of discharge, integrated environmental cyclic testing as simulation of aircraft use conditions, and self-discharge performance, was very good. The discharge performance for three out of the four design groups varied 7.7% from the nominal capacity for the 0.5C, 1C, and 2C discharge rates between –20°C and +50°C. The charge performance of all four groups varied 3.7% from the nominal capacity at charge rates of 0.5C, 1C, and 2C in the temperature range between –20°C and +23°C. Analysis of the test data led SAFT to select and propose one cell design to satisfy the performance requirements. The full performance range was projected to be achieved in the battery by using a heater blanket for the low temperatures and building in excess battery capacity for the higher military temperature range. Both of these engineering design methods were acceptable.

4.2 ELECTRO ENERGY, INC. (EEI) – BIPOLAR CELL DESIGN

The EEI cell data were questionable due to inconsistent results from a sealed test fixture for the larger 7x10 inch bipolar cells, questionable test methods indicated by the similarity of test results for different designed cells being tested together, and the significantly inconsistent test results among cell sets with identical designs and fabrication methods.

4.3 INTERIM TESTING CONCLUSIONS

The effort on the Ni-MH battery technology was intended to advance only one concept of a cell and battery design, either prismatic or bipolar. Both battery designs had advantages: the prismatic design was more mature but the bipolar design afforded more efficient packaging possibilities. Although the project was initiated with the strategy to select one source for the effort, when two strong and viable concepts were proposed, the Air Force decided to support both to reduce the technical development risk. However, as the project proceeded, the need to select one design for further support and advancement became necessary because of funding limitations.

The effort with SAFT America was continued. One prismatic cell design was selected and slight design changes were made based on the prior performance data to give four design alternatives. The data presented in the remainder of this report are limited to these four designs from SAFT America, called Serials, on the data graphs.

5.0 CHARACTERIZATION AND TESTING METHODS

Each subcontractor protected the technology and designs of the cells, materials, and manufacturing processes as proprietary. As a result, in the early phases of the project, the test methods and conditions were conducted differently by each subcontractor. These issues caused the data generated by each subcontractor on the different designs to be not comparable. Specific test conditions were discussed and identical test conditions were defined for each contractor that would provide performance data useful for direct comparison. However, some minor schedule slips and test fixture design differences resulted in some areas not being one-to-one comparable but still reasonably similar. The data that were lacking or incomplete were not critical to any priority design determinations nor programmatic decisions.

Specific test conditions were defined for charge and discharge capacity versus temperature, self-discharge over seven days, and ambient cyclic testing at 50% depth of discharge. The test schema and conditions are included with the data charts in section 5.0. A simulation of the flight checkout and engine starting conditions was conducted following the Integrated Environmental Cyclic Test from Lockheed Martin for the F-16. Exceptions to the conditions were taken to reflect expected use conditions and the fact that a cell rather than a production battery was being characterized.

5.1 CELL CAPACITY

The measurement of the capacity of the cell indicates the energy content available and an overall projection of performance. The bipolar and prismatic cell design alternatives early in the project were measured by the manufacturing company using their defined cell formation and test conditions. In order for GRCI to compare performance between the designs, a specific test plan was developed. Each manufacturing company reviewed and agreed to provide data in accordance with the matrix shown in Table 4.

The upper and lower test temperature range for the discharge performance are a +70°C high temperature test and a -30°C low temperature test. The -30°C test data were required but the +70°C was necessary only if needed to assist the discrimination between cells at the higher temperatures. Likewise, discharge performance at - 40°C was measured if data at the higher temperatures were not discriminatory.

After formation, the cell capacity measurement process cycle for the SAFT cells was defined as follows:

Discharge Rate vs Temperature
- Charge at 2 hours at C/2 + 3hours at C/20 at +23°C
- Rest 5 hours at the test temperature
- Discharge at the specified rate to 0.9V/cell
- Rest until reaching +23°C

Charge Rate vs Temperature
Rest 5 hours at the test temperature
Charge at the specified time and rate
Rest 5 hours in order to achieve +23°C
Discharge at C/2 to 0.9V/cell

As part of the cyclic test process, any residual charge in the cell was discharged at +23°C. Also, after each temperature test, a cell capacity check cycle was performed as follows:

Capacity Check Cycle at +23°C
Charge 2 hours at C/2 + 3 hours at C/20
Rest 15 minutes
Discharge at C/2 to 0.9V/cell
Rest in order to achieve +23°C

The charging process and charge monitoring studies performed later in the program provided specific charging algorithms for the test cells and batteries. Therefore, for the capacity measurements conducted later, the revised charging process determined for the test sets and batteries was used, as appropriate.

Table 4 Cell Capacity Measurements (after cell formation)

DISCHARGE PERFORMANCE				
	Discharge Temperature	**Cell Capacity, Ah** Discharge Rates to 0.9v/cell		
Standard Charge:		C/2	C	2C
C/2 @ Ambient	-30°C			
	-20°C			
	0°C			
	Ambient			
	+50°C			
	+70°C			

CHARGE PERFORMANCE		
Charge Temperature	**Charge Rate**	**Cell Capacity, Ah** (Standard Discharge: C/2 @ RT to 0.9v/cell)
-20°C	C/2	
	C	
	2C	
0°C	C/2	
	C	
	2C	
Ambient	C/2	
	C	
	2C	
+50°C	C/2	
	C	
	2C	

The material combinations and cell designs narrowed down as the project proceeded. The best performance was projected from four specific combinations of materials, designs, and processes. These four designs were considered most promising to satisfy the program objectives and were labeled as:

T3 – Serial 1
T3 – Serial 2
T3 – Serial 3
T3 – Serial 4

For each design a number of identical cells were fabricated. The cells then were put in either Group 1 for the cell capacity and self-discharge testing, or in Group 2 for the life cycle testing.

5.1.1 Discharge Performance

For each cell design, a set of six identical cells were fabricated from which the cell capacity measurements were taken as described above. The performance of the cell designs under conditions of discharging and charging over the temperature ranges of interest were measured. For discharge performance, Figures 3 to 8 give the cell capacity average and the cell voltage at 50% depth of discharge at each temperature. Figure 3 shows the excellent discharge performance from –30ºC to +70ºC for all four-cell designs. As the discharge rate increases from C/2 to 2C, the cell capacity is consistently high at 40Ah for three designs at –20ºC but drops to 30 Ah at +70ºC at the 2C rate of discharge as shown in Figure 7. The maximum cell capacity at each discharge rate remains at nominally 43 – 45 Ah at 23ºC.

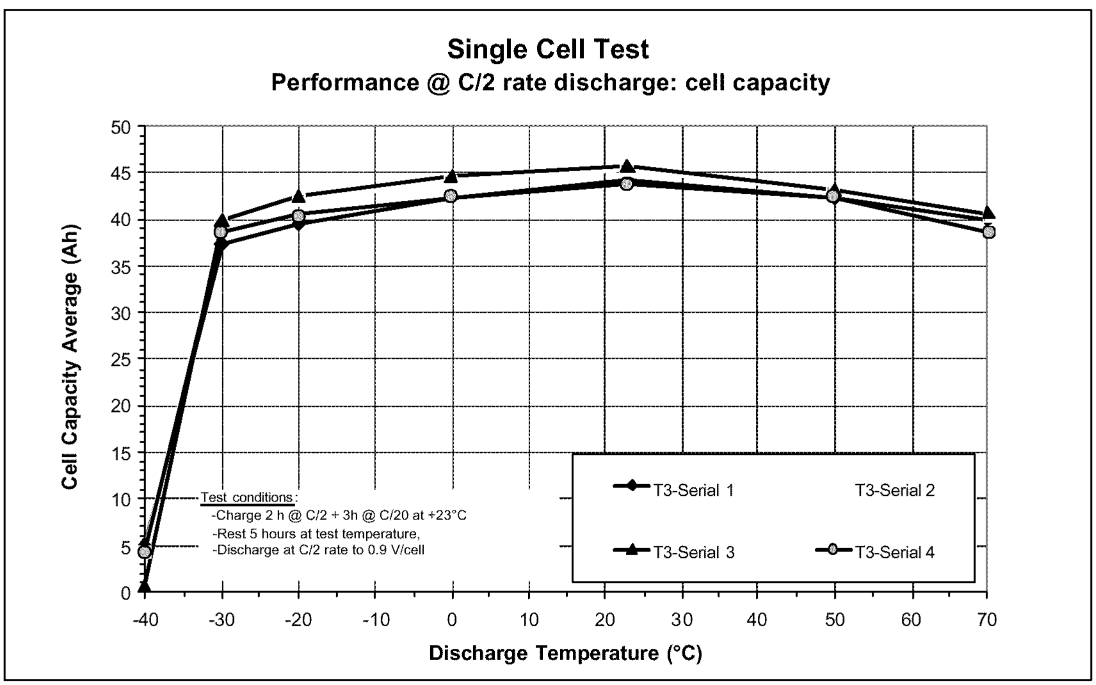

Figure 3 Cell Capacity vs Discharge Temperature for a C/2 Rate of Discharge

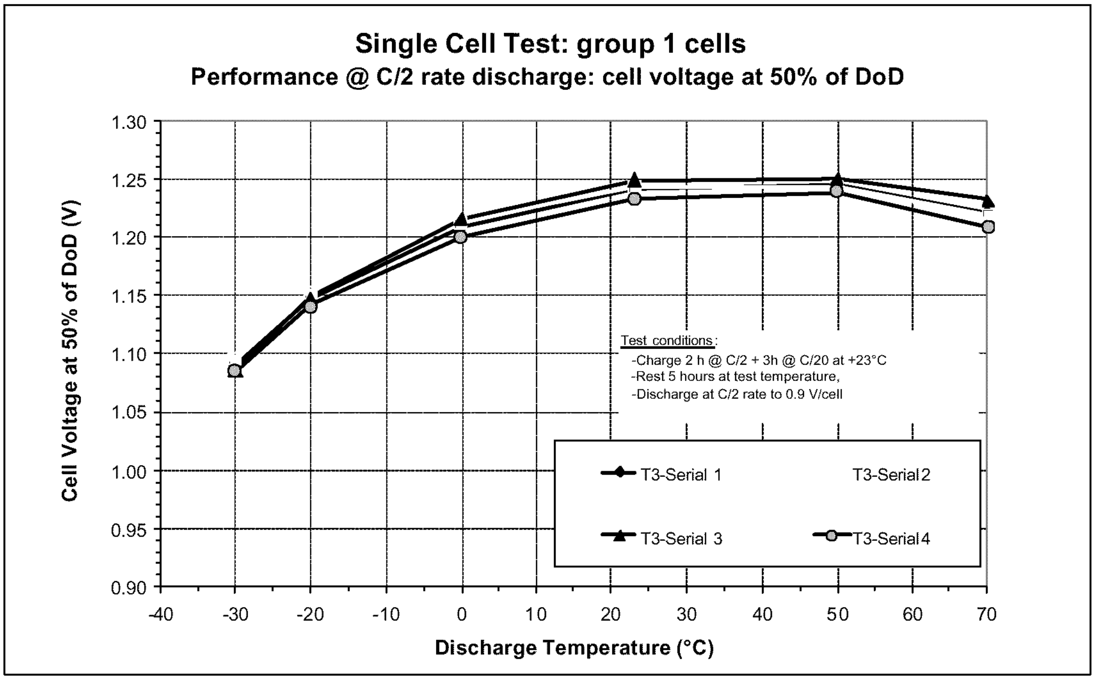

Figure 4 Cell Voltage at 50% Depth of Discharge vs Discharge Temperature for a C/2 Rate of Discharge

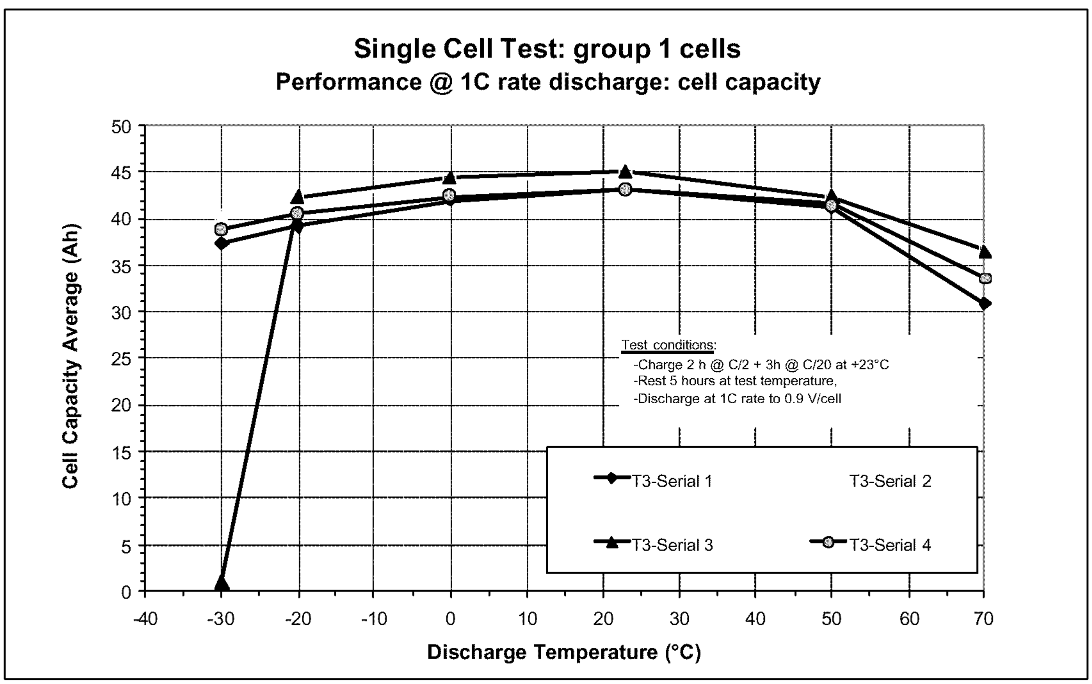

Figure 5 Cell Capacity vs Discharge Temperature for a 1C Rate of Discharge

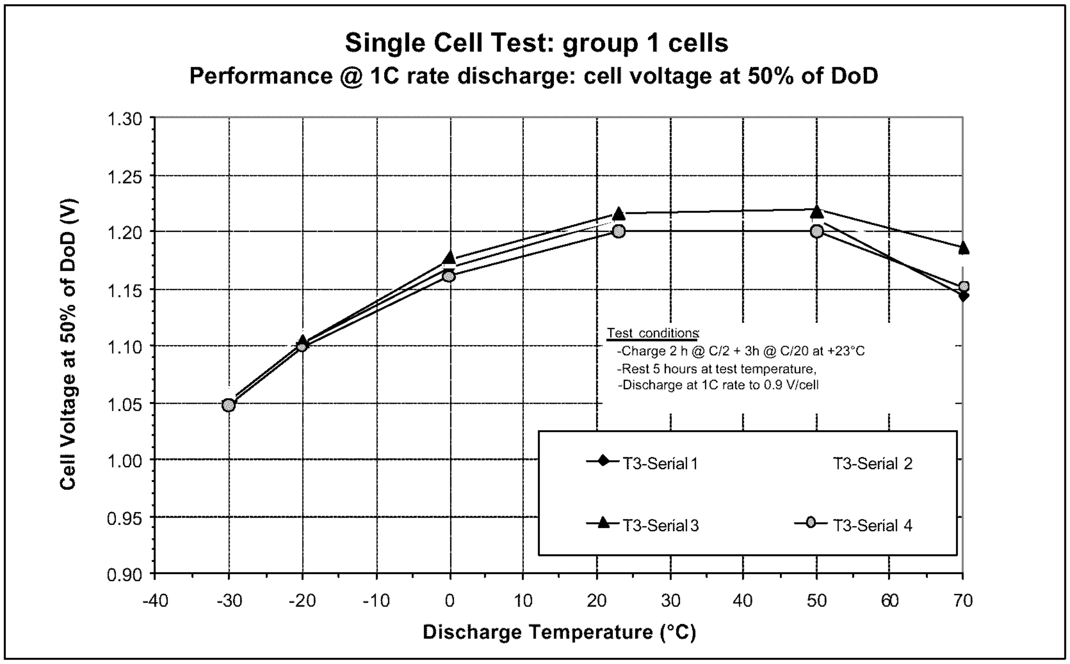

Figure 6 Cell Voltage at 50% Depth of Discharge vs Discharge Temperature for a 1C Rate of Discharge

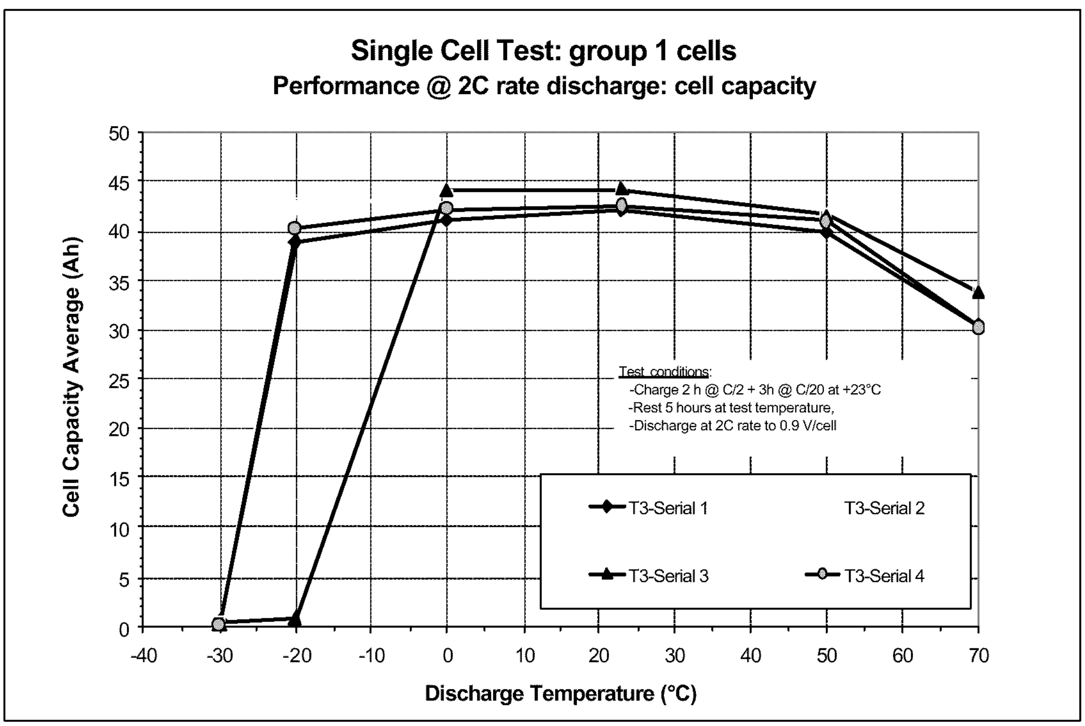

Figure 7 Cell Capacity vs Discharge Temperature for a 2C Rate of Discharge

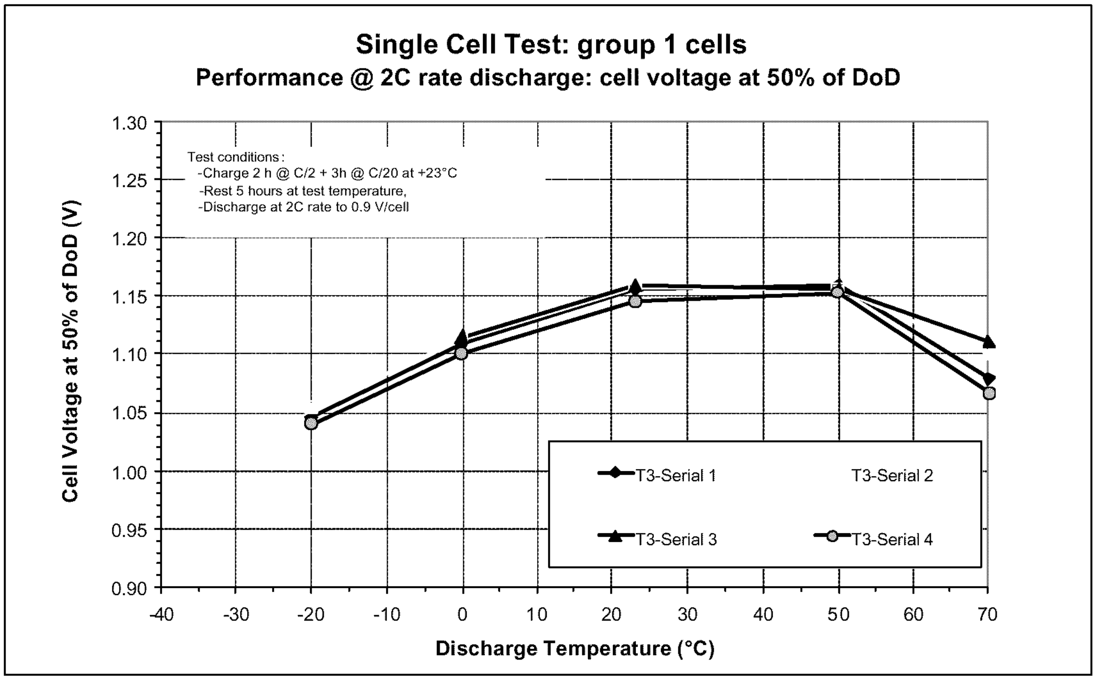

Figure 8 Cell Voltage at 50% Depth of Discharge vs Discharge Temperature for a 2C Rate of Discharge

5.1.2 Charge Performance

For each cell design, the same set of six identical cells that were fabricated and used in the discharge capacity tests were used for the charged capacity tests. However, during the series of discharge tests, two cells of the T3-Serial 3 design were damaged and were not available for charge performance testing. For charge performance, Figures 9 to 13 give the discharged cell capacity average and the end of charge cell voltage at each temperature.

Figures 9, 10, and 12 have similar characteristics showing stable charging performance over the lower temperature range up to +23ºC and dropping in charge performance at +50ºC with more dispersion at the 2C rate of charge. The end of charge cell voltage, Figures 11 and 13, is similar for both the 1C and 2C rate of charge dropping from 1.65 volts at –20ºC to 1.45 volts at +50ºC.

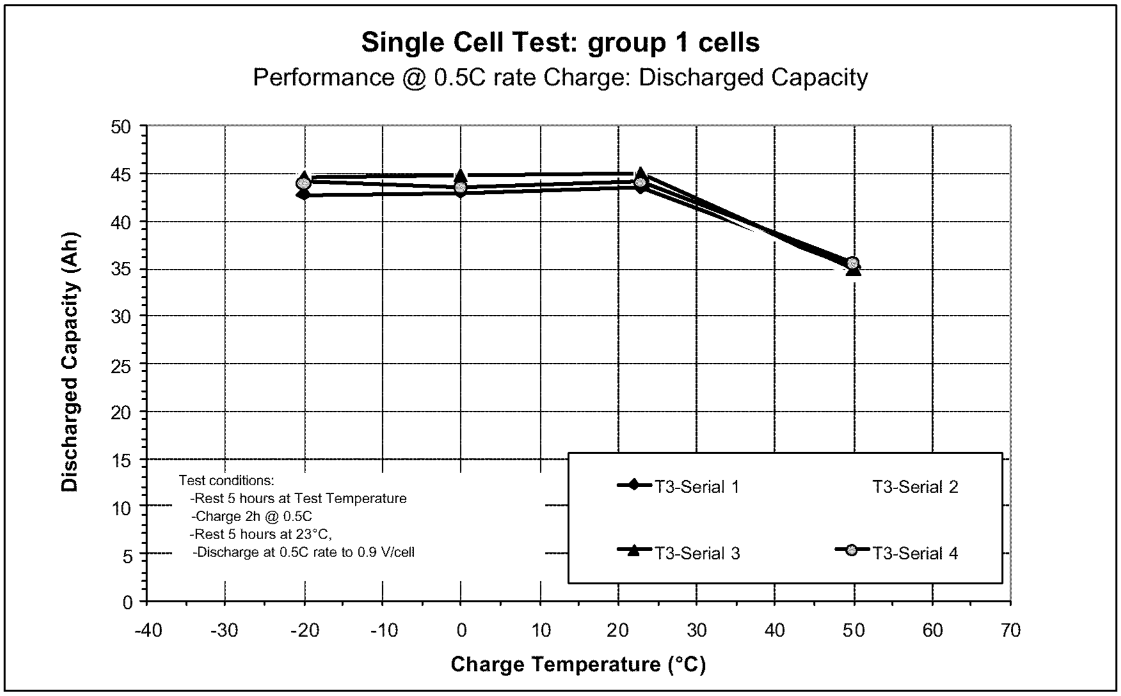

Figure 9 Discharge Capacity vs Cell Charge Temperature for C/2 Rate of Charge

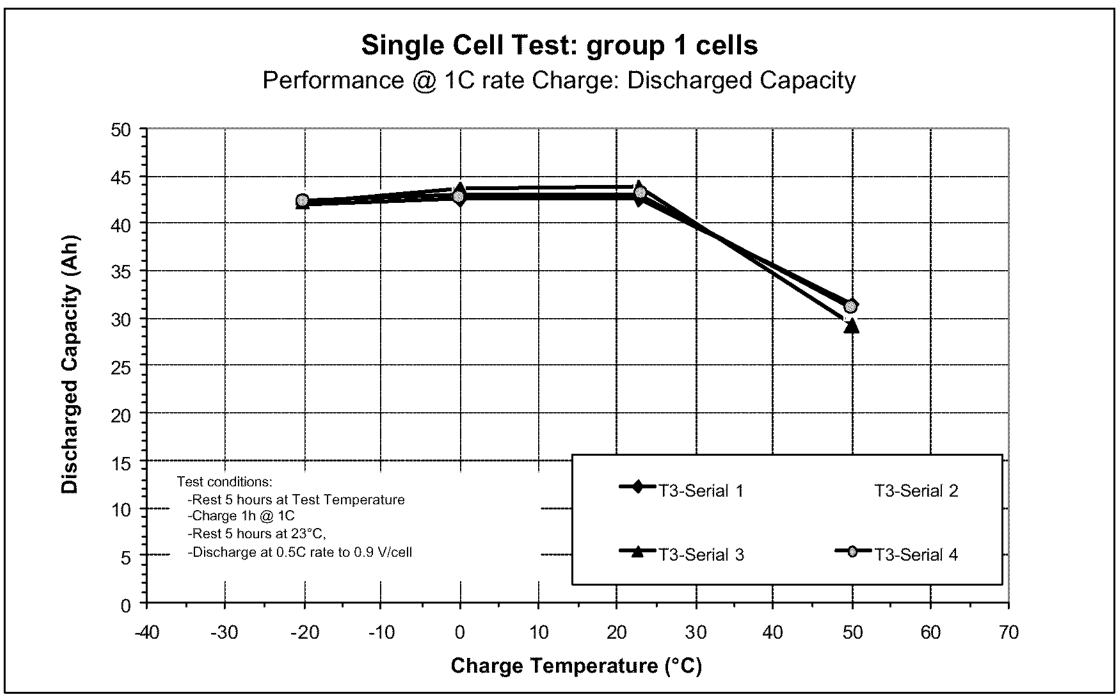

Figure 10 Discharge Capacity vs Cell Charge Temperature for 1C Rate of Charge

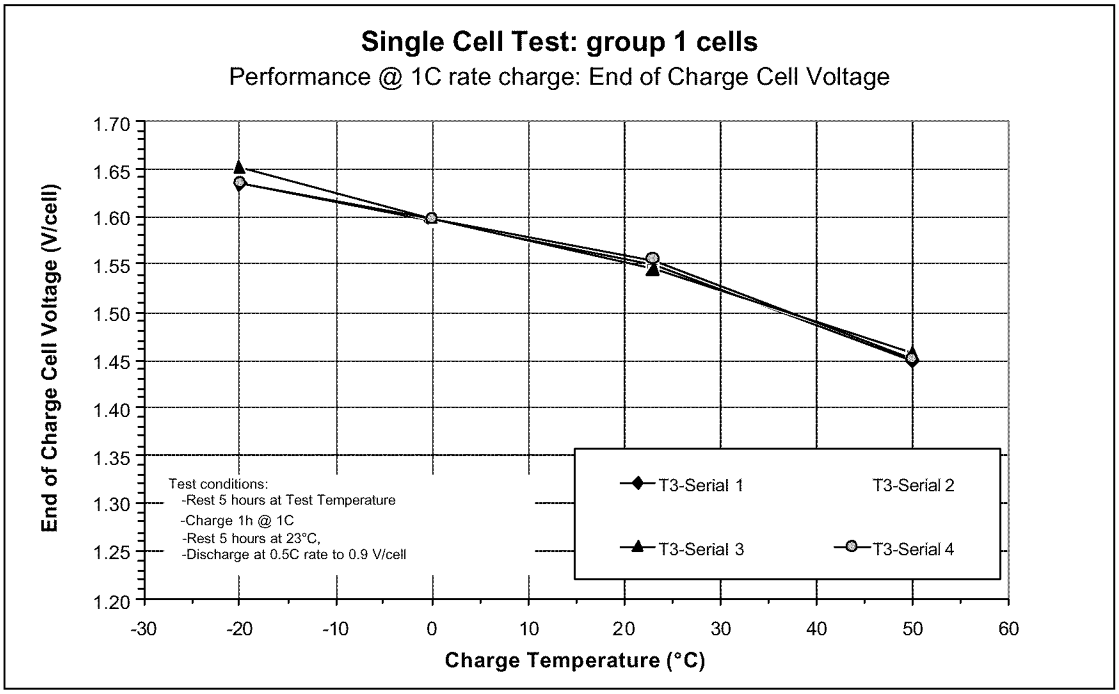

Figure 11 End of Charge Cell Voltage vs Charge Temperature for 1C Rate of Charge

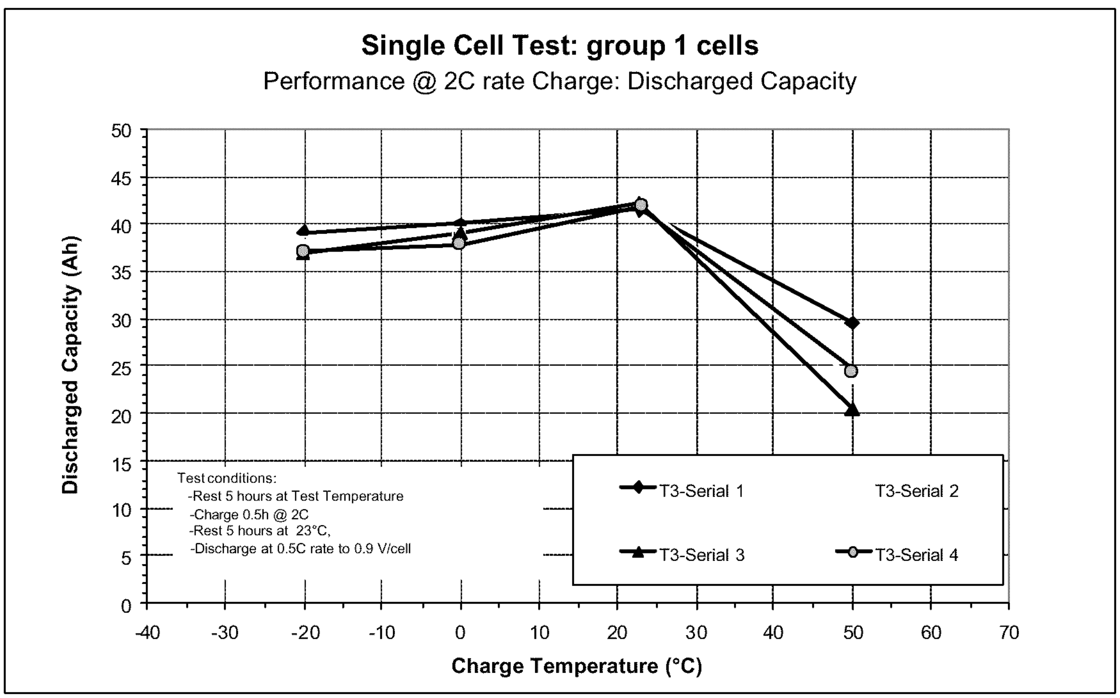

Figure 12 Discharge Capacity vs Cell Charge Temperature for 2C Rate of Charge

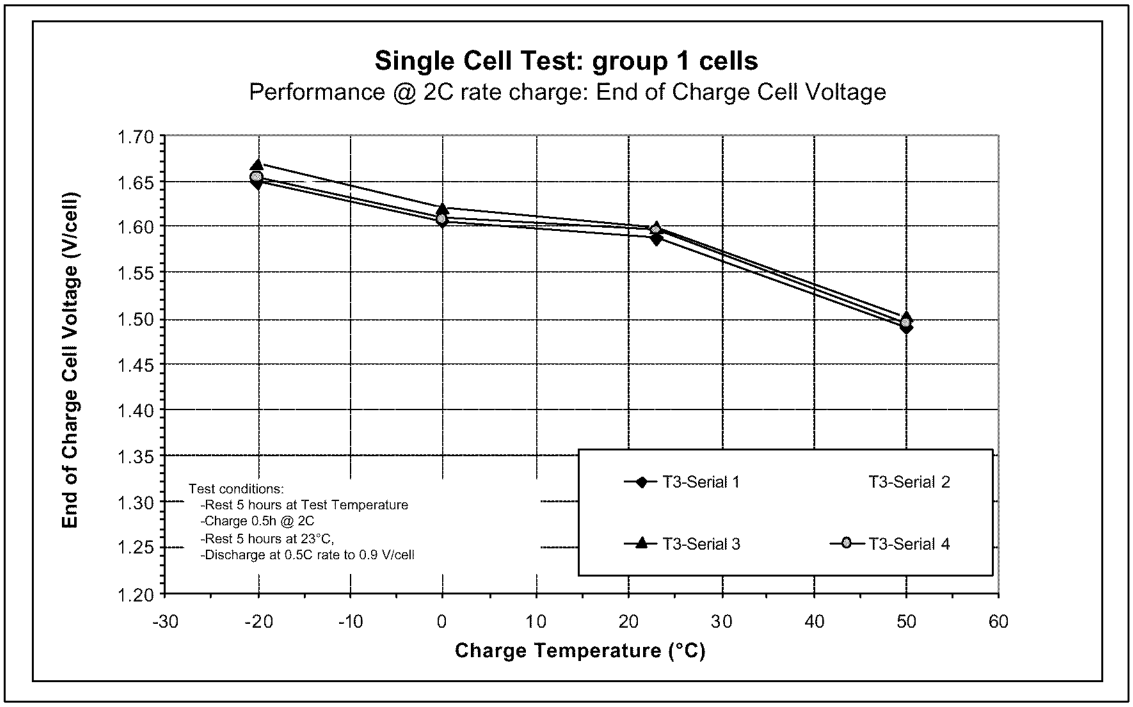

Figure 13 End of Charge Cell Voltage vs Charge Temperature for 2C Rate of Charge

5.2 SELF-DISCHARGE

Self-discharge performance was measured on all four-cell configurations over the temperature range of –10 to +50°C. The test arrangement was to fully charge the cells, expose the open circuit cells to the temperature of interest for seven days, and then measure the residual capacity. Determination of self-discharge performance required the following:

Determination of the initial capacity, C_i , at +23°C:

- Charge the cell for 2 hours at C/2 + 3 hours at C/20
- Rest 15 minutes
- Discharge at C/2 to the cut-off of 0.9V/cell

Determination of the residual capacity, C_r , after 7 days at the test temperature :

- Charge 2 hours at C/2 + 3 hours at C/20 at +23°C
- Open the circuit
- Age for 7 days at the test temperature, -10, 0, +23, +50°C
- Rest in order to achieve +23°C
- Discharge at C/2 to the cut-off of 0.9V/cell at +23°C

Calculation of self-discharge percentage:

$$\text{Self-discharge \% after 7 days} = \frac{(C_i - C_r)}{C_i} \times 100$$

Figure 14 is the self-discharge percentage versus temperature. The graph shows all designs satisfy a self-discharge percentage below 10% after 7 days at +23°C. However, only one design has a self-discharge percentage below 25% after 7 days at +50°C.

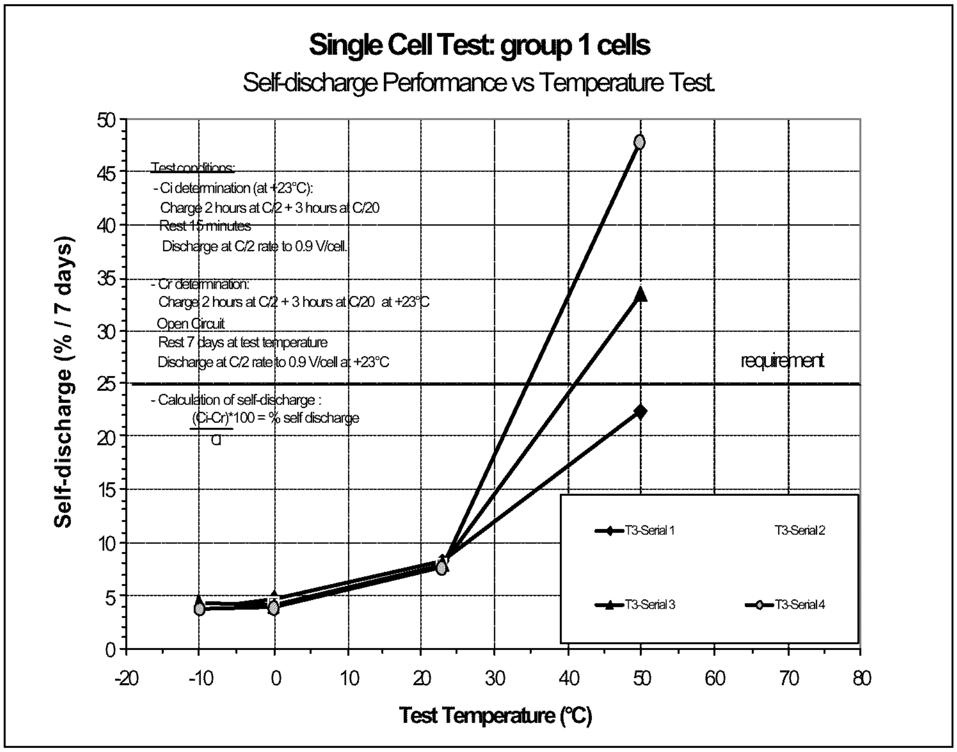

Figure 14 Self-discharge Over 7 Days vs Test Temperature for all Four Cell Designs

5.3 AMBIENT LIFE CYCLE TESTS

A correlation of cell and battery performance to system requirements was required by the project. Life cycle tests are considered to be a laboratory simulation or exposure to the use environment. Two types of life cycle tests were defined to be conducted in sequence. Ambient Life Cycle Tests with a 50% depth of discharge were conducted early to provide data allowing a down-selection of the best candidate cells for use in the Integrated Environmental Cyclic Tests.

Subcontractor defined Ambient Life Cycle Tests were conducted early in the program by the manufacturing companies on the bipolar and prismatic cell design alternatives. The companies tested their designs to different conditions that were not comparable. One company tested at 75% depth of discharge while the other tested at 20% depth of discharge. In order for GRCI to compare performance between the designs, a specific test plan was developed for 50% depth of discharge. Specific design and performance differences were recognized to result in unique test condition requirements for discharging and overcharging, for example. Any cell design's specific test conditions were described by the subcontractor and included in the Test Plans delivered with the test samples.

To compare performance data between the subcontractors, the Ambient Cyclic Tests at 50% depth of discharge were specifically defined. Due to cell design and testing methods, the testing procedures were not identical. However, each test cell attained ambient temperature between cycles to eliminate any thermal effects in subsequent cycles. To eliminate the thermal effects, a rest period in the test sequence was required. In addition, active cooling meth-

ods to attain ambient temperature in less time were acceptable and were specified by the subcontractor as part of the test method.

The test procedure used by SAFT for the Ambient Cyclic Tests at 50% depth of discharge was based on cells having an initial capacity of nominally 10 Ah. Each cell was fully charged using 2 hours at C/2 + 3 hours at C/20. The Ambient Cyclic Test procedure was as follows:

> Discharge for 30 minutes at 1C
> Rest 30 minutes
> Charge for 1 hour at C/2 + 1 hour at C/20
> Rest 10 minutes
> Repeat Cycle

The cells were fan-cooled during the entire ambient cyclic test sequence. The rest period allows the cell to attain ambient temperature prior to next test cycle.

After every 50 cycles, a measurement of capacity was made using the following method:

> After the discharge at 30 minutes at 1C in the 50^{th} cycle, fully discharge the cell at C/2 to 0.9V/cell.
> Charge the cell 2 hours at C/2 + 3 hours at C/20
> Rest 15 minutes
> Discharge at C/2 with cutoff at 0.9V/cell

The cells were fan-cooled during the capacity check test sequence. Following the capacity check, each cell was fully charged using 2 hours at C/2 + 3 hours at C/20. Then the cyclic tests were continued for an additional 50 cycles. The cell and battery performance was considered failed if the discharge capacity became less than 75% of the nominal or initial capacity. Likewise, failure was indicated if the voltage was less than 0.9V/cell or 75% of the battery nominal voltage.

The cyclic performance over 200 cycles for the cell designs is given in Figure 15 and Figure 16. No degradation of performance was apparent during this testing sequence. A full cyclic test scheme of a minimum of 600 cycles was planned but not accomplished due to the time available within the program. With the performance of the cells in other tests at ambient temperatures showing no detrimental response at +23ºC, there was limited risk in the assumption that further testing would result in a decrement of cell capacity performance. However, full cyclic testing should be accomplished on the final cell configuration or the complete battery design to establish a projection of cyclic lifetime.

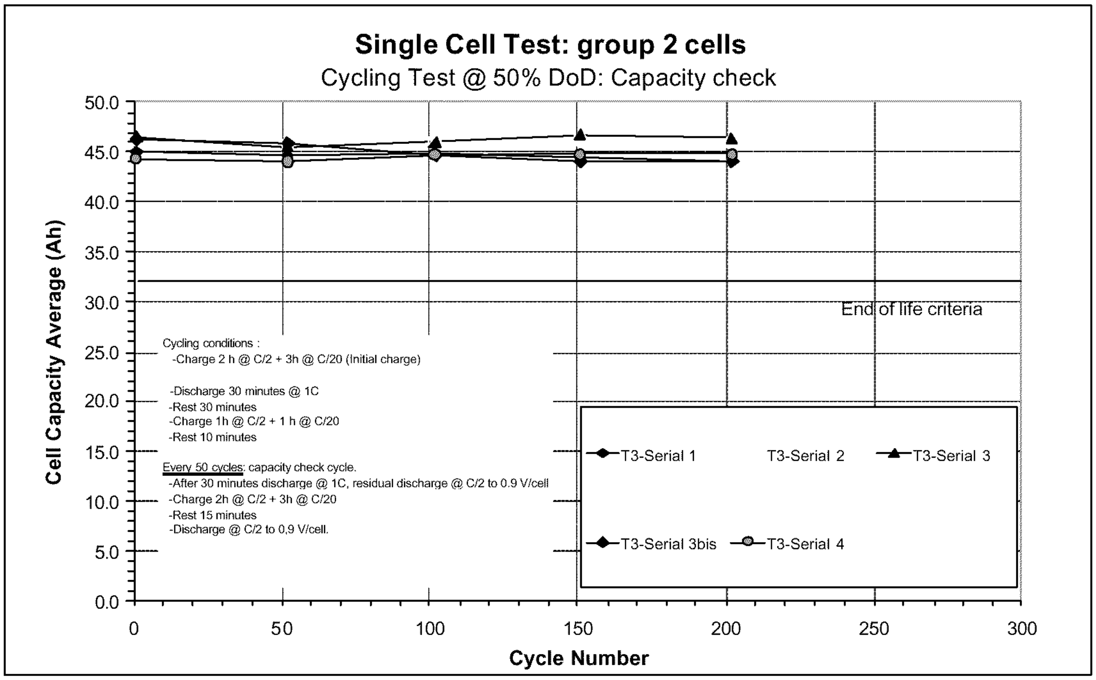

Figure 15 Capacity Check Every 50 Cycles Measured by Cell Capacity vs Cycle Number for Each Cell Design

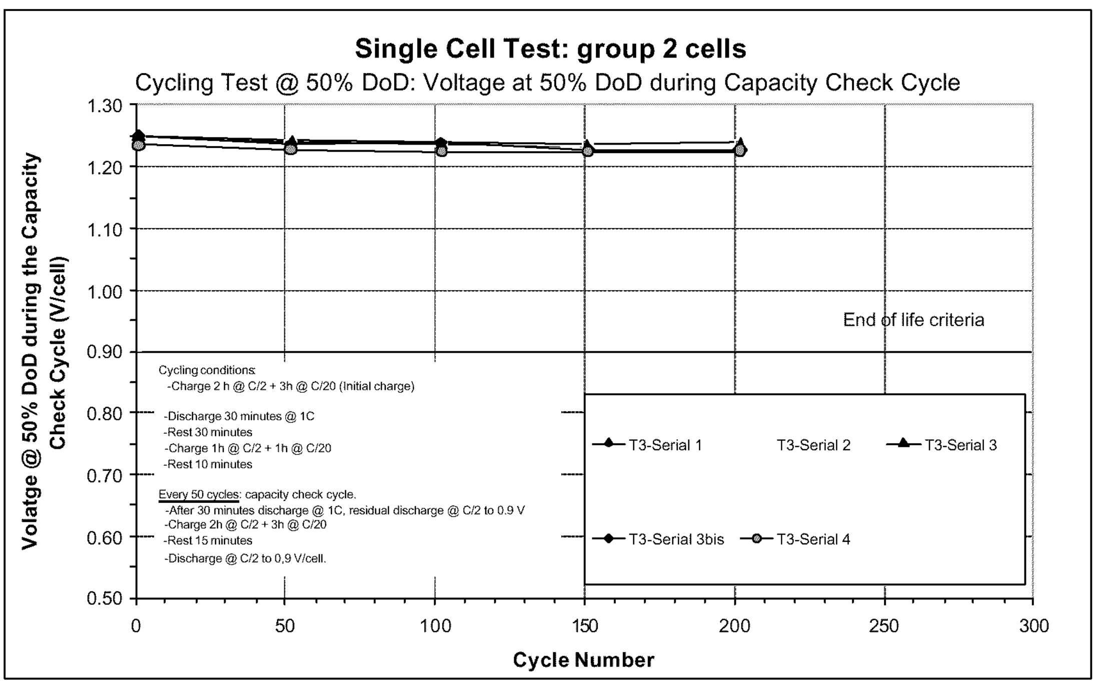

Figure 16 Cell Voltage at 50% Depth of Discharge During the Cell Capacity Check for each Cell Design

5.4 INTEGRATED ENVIRONMENTAL CYCLIC TESTS

The Integrated Environmental Cyclic Test is a set of 80 cycles defined by the Lockheed Martin Spec #16ZE374B, 18 June 1993. The 80 cycles simulate the battery conditions experienced during flight checkout and engine start over the thermal conditions projected in worldwide operations for the F-16.

Figure 17 is a graphical representation of the 80-cycle test sequence, test conditions, and the type of test to be conducted. Table 5 is extracted from the specification and explains the different types of tests.

For this effort, the test conditions were adjusted from those defined in the battery specification to adapt to the size of the bipolar and prismatic cells. Earlier, the capacity data showed the cells had minimal if any discharge performance at – 40°C. In addition, the cells would not be used singly but only in a battery configuration that would have a heating blanket. As a consequence, the test temperatures for the lower temperatures in the Integrated Environmental Cyclic Test were changed as follows:

> -29°C changed to -18°C, and
> -40°C changed to -29°C.

The defined test sequence was not changed. The defined rest period between cycles was recommended in the specification to be between 4 – 24 hours. The thermal response of the equipment and the test samples was evaluated. For the single cell tests, a two-cell test +70°C and cooled to -40°C in a climatic chamber. The cell was monitored and allowed to reach equilibrium at each temperature then the chamber was set to +23°C. The test sample reached the test temperature in nominally 5 to 6 hours with a thermal delay of the chamber being 25 minutes to reach +70°C and 45 minutes to reach – 40°C. When the chamber was set to +23°C, the test cell stabilized at +23°C in less than 4 hours for both temperatures. Therefore, the rest period for the test procedure was not less than 4 hours.

As an example for the Integrated Environmental Cyclic Test, assuming the cell is fully charged, the cyclic set of conditions at -18°C for a single cell would be

> Rest 4 hours to stabilize the cell at – 18°C.
> Discharge at – 18°C at 20A for 10 minutes or until cut-off of 0.9V/cell.
> Charge at – 18°C according to the determined conditions for the cell.
> Repeat the cycle in accordance with the test plan.

The test procedure for the periodic capacity check at +23°C following the last cycle of a set was

> Rest for 4 hours to stabilize the cell temperature at +23°C.
> Discharge at 20A until reaching the cut-off of 1.0V/cell.
> Charge at 20A according to the determined conditions for the cell.
> Begin the next set of cyclic testing conditions.

Figures 18 and 19 present the Integrated Environmental Cyclic Tests data in terms of cell voltage and cell capacity, respectively, for the complete 80 cycle sequence. No irregular data were generated. The cells performed well and satisfactory under the entire cyclic test sequence.

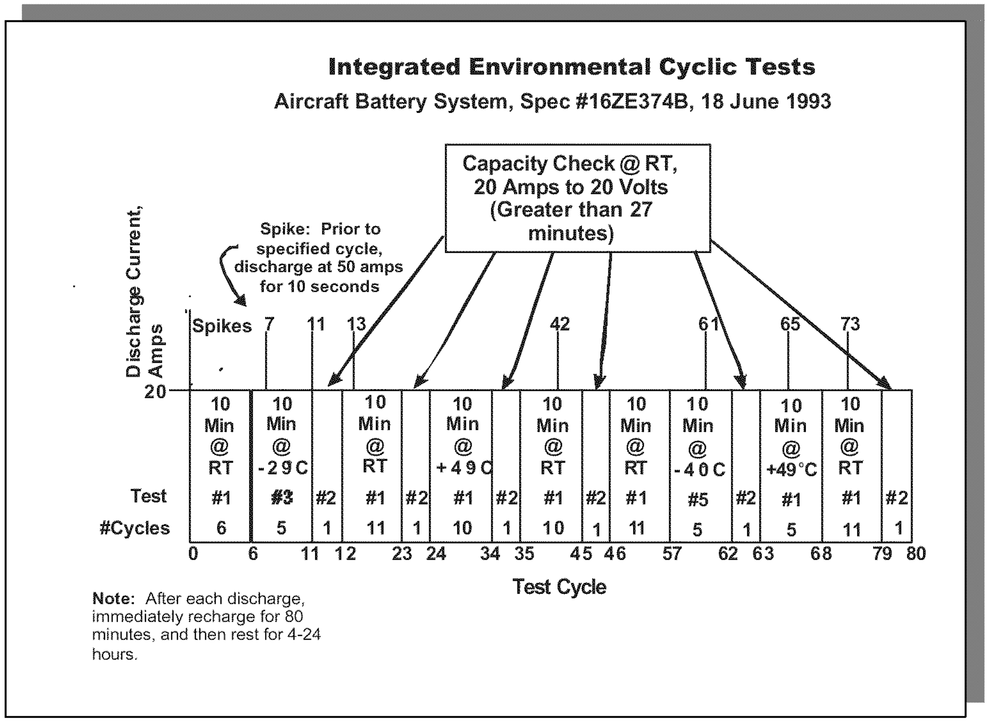

Figure 17 Test Scheme for Flight System Profile
(for Vented Ni-Cd Battery Charger Performance)

Table 5 Descriptions of Test Conditions for Flight System Profile with Reference to Figure 17 (Aircraft Battery System, Spec #16ZE3743B, 18 June 1993)

#1 Normal Discharge

a. Discharge battery at 20 Amps for 10 minutes. (3.3 Ah)
b. Immediately recharge for 80 minutes.
c. Rest for 4 - 24 hours.

#2 Capacity Check

a. Discharge battery at 20 Amps to 20 volts.
The discharge time must be greater than 27 minutes.
b Immediately recharge for 80 minutes.
c. Rest for 4 - 24 hours.

#3 Cold Temperature Discharge

a. Discharge battery at 20 Amps for 10 minutes. (3.3 Ah)
b Immediately recharge for 80 minutes.
c. Rest for 4 - 24 hours.

#5 Extreme Cold Temperature Discharge

a. Discharge battery at 20 Amps for 10 minutes. (3.3 Ah)
b Immediately recharge for 80 minutes.
c. Rest for 4 - 24 hours.

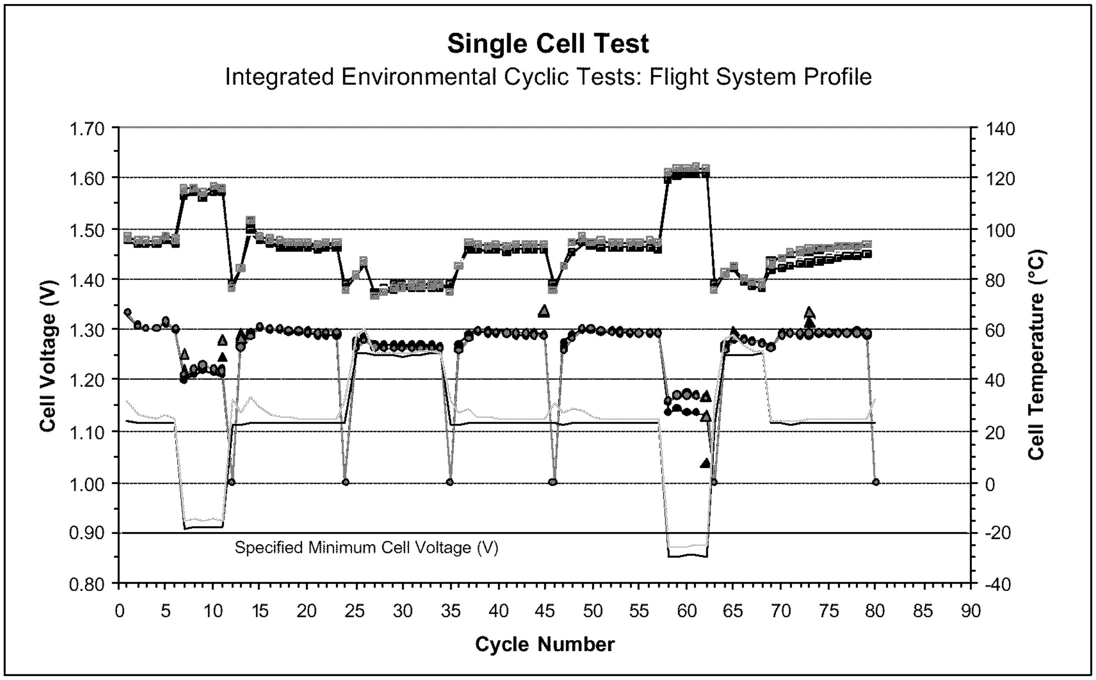

Figure 18 Bottom Curve: Cell Voltage after Discharge Cycle at Corresponding Temperature. Top Curve: End of Charge Cell Voltage Prior to Next Cycle at Corresponding Temperature

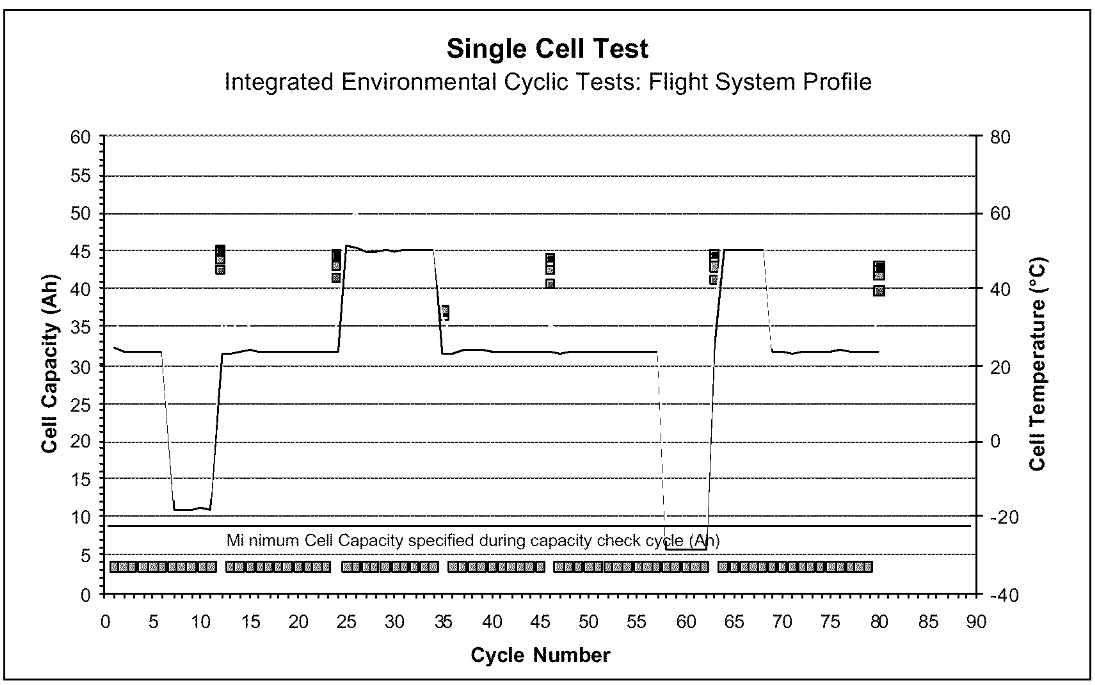

Figure 19 Cell Capacity Check at +23ºC after Designated Cycle Number

6.0 TEST SET

Independent evaluation and confirmation of cell performance was required by the Air Force. The battery test laboratory of the AFRL Propulsion Directorate has the capability for evaluation of test cells. Four prismatic cells were assembled together as a test set, Figure 20. Stiffened end plates and compression straps held the four cells together and sandwiched a thermistor between each cell for temperature monitoring during testing. Three sets of four cells were delivered for test and evaluation. Special handling and safety requirements were used during all characterization.

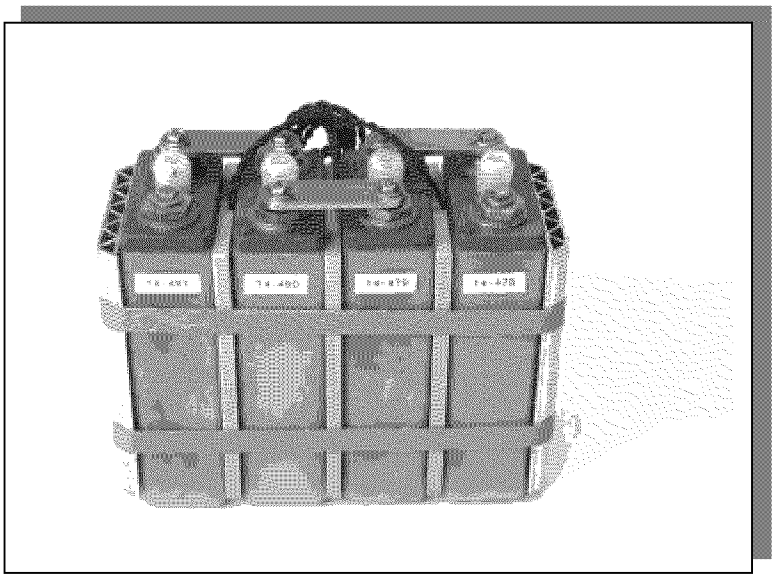

Figure 20 Test Set of Four Ni-MH Prismatic Cells From SAFT

7.0 PRE-PROTOTYPE BATTERY ASSEMBLY

The Ni-MH batteries included 20 individual cells assembled into a case with a connector and heater blanket. The pre-prototype battery was delivered with a test plan definition similar to that provided with the test cells. Figure 21 is the assembled battery showing the cells and the interconnections between the cells. Figure 22 is the fully assembled and sealed Ni-MH pre-prototype battery.

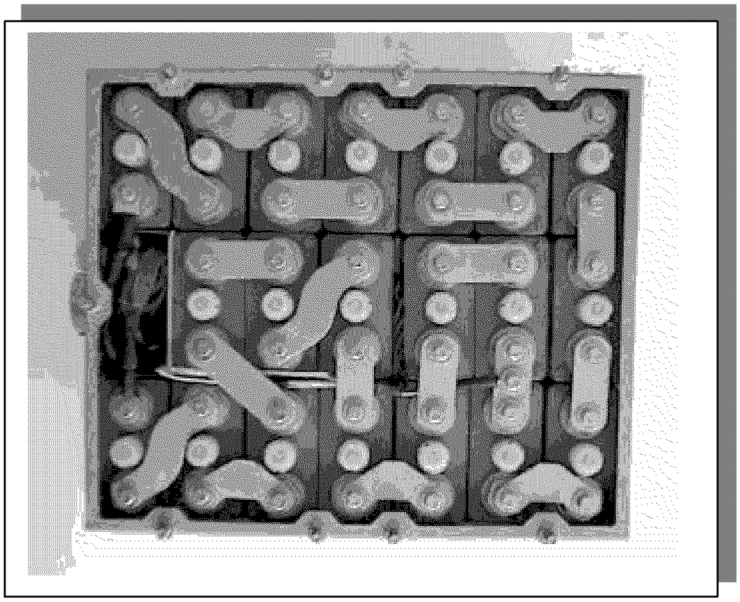

Figure 21 Layout and Interconnections of the 20 Cells in the Pre-Prototype Battery

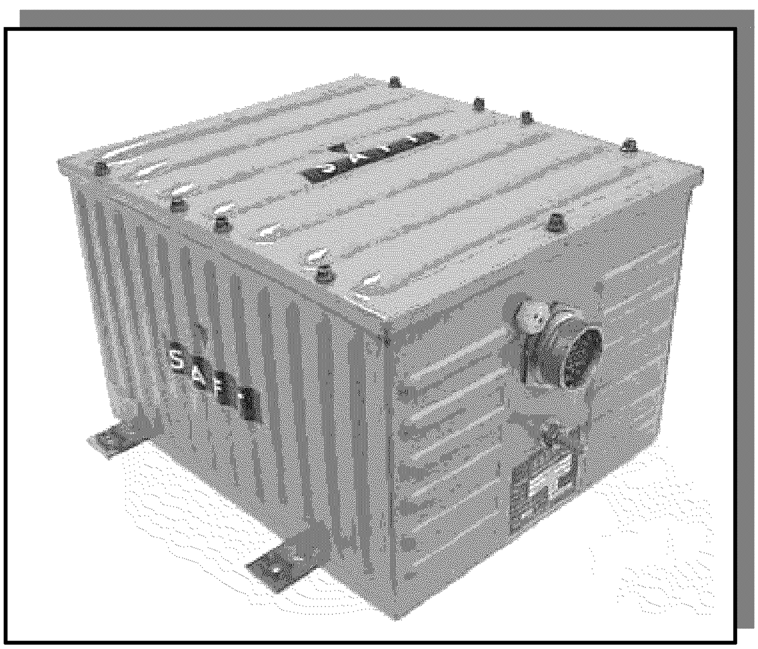

Figure 22 Fully Assembled and Sealed Ni-MH Pre-Prototype Battery With Connector

8.0 SUMMARY

Nickel-Metal Hydride prismatic cells have been designed, fabricated, and characterized for performance across the temperature range of – 40°C to +70°C. The optimized designs were validated in controlled laboratory conditions and under simulated environmental testing conditions. All aspects of the cells were evaluated and selected optimization was designed into the cells to advance the Ni-MH technologies to attain the program target goals. Electrode formulations, processes, electrolyte percentages, separator materials and thickness, and assembly were evaluated in specific cell design configurations. The charging procedure and algorithms were determined and implemented. These test and evaluation conditions were recommended for repeatable charging and safety limits to independently confirm the performance of the prototype designed battery. One pre-prototype battery will be delivered to the Air Force having approximately 64Wh/kg using cells with 43Ah capacity at C/2. Among the key performance variables for this next generation battery are broad temperature range and minimal self-discharge. Both key performance variables were enhanced sufficiently to make the Ni-MH battery technology a strong alternative to conventional battery power sources in military flight vehicles.

The characteristics and performance parameters of the pre-prototype battery were designed using the data derived during the effort. Table 6 presents the parameters of the pre-prototype battery delivered under this project. The parameters confirm the capabilities of Ni-MH battery technology to satisfy military aircraft battery power requirements while also having no contamination of the environment from heavy metals.

Table 6 SAFT Ni-MH Battery Parameter Values Achieved

Nominal Voltage (V)	24
Rated Capacity (Ah)	43
Current (A)	48
Operating Temperature Range (°C)	-40 to +71 (with heaters)
Typical Battery Energy at C/2 (Wh)	1,126
Typical Specific Energy Density (Wh/kg)	64
Typical Volumetric Energy Density (Wh/l)	127
Total Battery Weight (kg {lb})	17.7 {39}
Maintenance Interval	Maintenance Free
Self-Discharge (<25% over 7 days)	25% for T < 40°C

9.0 REFERENCES

1. Erbacher, J. K. and Vukson, S. P., Proceedings of the 38th Power Sources Conference, Cherry Hill, NJ, 1998, pp. 111-114.
2. Erbacher, J. K., "An environmental aircraft battery (EAB)," *J. Power Sources,* **80**, (1999) 265-271.